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Princeton, New Jersey

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Vibroscope Measurements of the Elastic Moduli of Nylon 66 and Dacron Filaments of Various Draw Ratios

by

J. H. Wakelin, E. T. L. Voong, D. J. Montgomery
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Abstract

By use of the electrostatic vibroscope method, dynamic measurements have been made of the Young's modulus derived from bending and the torsional modulus of nylon 66 and Dacron filaments ranging in draw ratio from one (undrawn) to six. Quasi-static measurements have also been made to obtain the Young's modulus derived from extension. The dynamic values of the Young's modulus increase from draw ratio one to draw ratio six by a factor of 3.5 for nylon 66 and 5.8 for Dacron. The torsional moduli of both filament types exhibit no appreciable changes with increasing draw ratio.

The ratio of the Young's modulus to three times the torsional modulus, which ratio is unity for a homogeneous isotropic material with a Poisson's ratio of 1/2, is about three for nylon 66 and greater than five for Dacron at a draw ratio of six. These results, along with those obtained at lower draw ratios, indicate that both filaments become progressively anisotropic with drawing, the extent of the anisotropy reflecting mainly the changes in the Young's modulus. As a check on the experimental procedures, the elastic moduli have also been measured for a 1-mil drawn tungsten wire.

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Introduction

The Young's modulus and torsional modulus of nylon 66 and Dacron filaments of various draw ratios have been determined with the electrostatic vibroscope technique [1]. The vibroscope method used for measuring the bending modulus of the filaments is essentially similar to that described by Lochner [2] and Kärrholm and Schröder [3]. The principal change in the present technique is the application of the electrostatic method for exciting the filaments' oscillations rather than the mechanical one described by these authors. The method for measuring the torsional modulus differs from that described and used by Ray [4], Meredith [5], and by Hammerle and Montgomery [6] in that the electrostatic vibroscope method was used to drive the filament in forced torsional vibration at frequencies comparable with those of the bending vibration. Values for the Young's modulus for these filaments were also obtained by extending filaments at a constant rate of extension. The ratio of Young's modulus derived from extension and from bending to three times the torsional modulus has been used as an indication of anisotropy of the nylon 66 and Dacron filaments of various draw ratios. For a homogeneous, isotropic, incompressible elastic body, this ratio is unity. Increasing departures of this ratio from unity represent increasing structural anisotropy. Such increasing anisotropy may be expected with increasing draw ratio.

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Description of Samples

Samples of nylon 66 and Dacron were prepared and supplied to Textile Research Institute by the Textile Fibers Department of E. I. du Pont de Nemours and Company. The draw ratios of both filament types were 1.00 (undrawn), 2.02, 2.99, 3.99, 5.02, and 5.99. Samples of 1-mil drawn tungsten wire were also studied to determine the Young's modulus from both extension and bending, and to determine the torsional modulus in order to compare with similar values obtained on the undrawn filaments of the nylon 66 and Dacron series. The samples of tungsten wire were obtained from the Palmer Physical Laboratory, Princeton University, Princeton, New Jersey and from the Cleveland Wire Works, Lamp Division, General Electric Company, Cleveland, Ohio.

Experimental Procedure

Filaments of nylon 66 and Dacron for the draw ratios one to six inclusive were mounted on cellulose acetate tabs to provide a test length of 7-10 cm. The length of the fiber between tabs was measured with a low-power travelling microscope reading to 0.0001 cm. The mass per unit length of these filaments was then determined with the electrostatic vibroscope; a correction for filament stiffness was also made [7, 8]. All measurements were conducted on samples conditioned to a temperature of 70°F and a relative humidity of 65%.

Torsion.--A short length of 30-denier nylon 66 filament (0.40 cm) was mounted with Duco cement as a cross-bar on the center of and transverse to the length of the filament described above. The filament with cross-bar attached (Figure 1) was then clamped in a vertical position; the lower tab was restricted from rotating by clamping a metal cross-bar to the

lower tab and restricting the rotation of this cross-bar by two small pegs. The cross-bar at the center of the filament under test was then set into oscillation by placing one end between electrodes, as shown in Figure 1. The electrodes were mounted in a horizontal plane and were energized by an audio-frequency generator as in the original vibroscope method. A d.c. bias of 300 volts was used to place a charge on the filament.

The frequency of torsional response of this system is [9]:

$$\nu^2 = \frac{3\, G\, d^4\, g\left(\frac{1}{\ell_1} + \frac{1}{\ell_2}\right)}{32\, \pi \rho'\, S'\, L'^3} \qquad \text{- - - - - - - - - - - - - - (1),}$$

where ν is the frequency (cps),

G is the torsional modulus (gm/cm^2),

d is the diameter of the filament (cm),

g is the gravitational acceleration (cm/sec^2),

ℓ_1 and ℓ_2 are, respectively, the lengths of the filament above and below the cross-bar (cm),

ρ', S', and L' are, respectively, the density (gm/cm^3), cross-sectional area (cm^2), and length (cm) of the cross-bar.

From Equation 1 the torsional modulus G may be expressed as:

$$G = \frac{32\, \pi \rho'\, S'\, L'^3 \nu^2}{3\, d^4\, g\left(\frac{1}{\ell_1} + \frac{1}{\ell_2}\right)} \qquad \text{- - - - - - - - - - - - - - (1a).}$$

In contrast with the case of bending, where the distributed parameters lead to a differential equation permitting various modes of oscillation, the case of torsion, with its lumped parameters, leads to an ordinary differential equation with only one mode of oscillation.

Moreover, the torsional frequency should be independent of filament tension, provided that such tension does not appreciably affect the torsional modulus. Data were obtained to show the independence of the frequency response to changes in filament tension; such data for a sample of 30-denier drawn nylon 66 filament are plotted in Figure 2. The change in frequency with various values of $\left(\frac{1}{\ell_1} + \frac{1}{\ell_2}\right)$ was also investigated with samples of the same nylon filament. The results shown in Figure 3 confirm the validity of Equation 1.

Bending -- After the torsional modulus G was obtained by the cross-bar method, the Young's modulus Q by bending was measured on the length of filament below the cross-bar. In fact, this lower length of the filament was cut in two so that duplicate measurements of Q could be obtained. In these measurements the free end of the filament was placed between the electrodes of the vibroscope, as shown in Figure 4, and the magnified image of the fiber viewed through a low-power microscope. The filament length from the tab to the free end was then read to 0.0001 cm. The mass per unit length of each test length used (prior to cutting in two) was determined by a separate vibroscope measurement. The natural bending frequencies of the filament are [10]:

$$\nu_n = \frac{\pi}{2L^2}\sqrt{\frac{Q\,K^2\,g}{\rho}}\cdot\beta_n^{\;2} \qquad \text{- - - - - - - - - (2),}$$

where ν_n is the frequency of the n^{th} allowed frequency (cps),
ν_1 is the fundamental, ν_2 is the first overtone, etc.,
L is the length of the filament (cm),
Q is the Young's modulus (gm/cm^2),
g is the gravitational acceleration (cm/sec^2),
ρ is the filament density (gm/cm^3),

K is the radius of gyration of the cross-section (cm); for a filament with a circular cross-section of diameter d, K = d/4,

β_n is a dimensionless constant for the n^{th} allowed frequency; $\beta_1 = 0.597$, $\beta_2 = 1.494$, $\beta_3 = 2.500$, etc.

The value of the Young's modulus, Q, from Equation 2 is:

$$Q = \frac{64\ L^4 \rho \nu_n^{\ 2}}{\pi^2\ d^2 \beta_n^{\ 4} g} \qquad \text{- - - - - - - - - (2a).}$$

For a filament of circular cross-section,

$$\nu_1 = \frac{0.55966d}{4L^2}\sqrt{\frac{Qg}{\rho}} \ ,$$

$$\nu_2 = 6.267\,\nu_1 \ ,$$

$$\nu_3 = 17.548\,\nu_1 \ ,$$

$$\nu_4 = 34.387\,\nu_1 \ , \text{ etc.} \qquad \text{- - - - - - - - - (3)}$$

The change of frequency with the order of the overtone for a given length of filament, and the change in frequency with filament length at a given order of overtone, have been measured on 30-denier drawn nylon 66. These results are plotted in Figure 5 and are found to be in conformity with the prediction of Equation 3. The effect of air damping has not been studied as such, but the frequency-sample length variations in the test conditions both for bending and torsion indicate that no appreciable effects of air damping are noticeable. The present work was conducted in a frequency and filament-denier range beyond that found to be critical for air damping effects by Kärrholm and Schröder.

Extension -- The Young's modulus E from extension was determined on the length of filament between the cross-bar and upper support by

means of the Instron Tensile Tester. For nylon 66 and Dacron, sample lengths of about 2.5 cm. were extended at a constant rate of 50%/min. For tungsten wire with test lengths in the 4-10 cm. range, the range of extension rates was from 0.5%/min. to 2%/min. The mass per unit length of each test sample was obtained by a separate vibroscope measurement.

Experimental Results and Discussion

The data for the Young's modulus (E) from extension and (Q) from bending and the torsional modulus (G) for nylon 66 and Dacron filaments are presented in Tables 1 and 2 and plotted in Figures 6 and 7. The values reported are means of measurements on four filament samples for E and G and on eight for Q. The tolerances in these and in succeeding tables are deviations of the mean values at the 95% confidence limits. The Young's moduli from extension and from bending increase by a factor of approximately four for nylon 66 and six for Dacron from the undrawn state to a draw ratio of six. The values for E are generally lower than those for Q. This difference is undoubtedly due to the relatively large effect of creep and stress relaxation during the extension of the filaments to obtain E.

As a check on the vibroscope method for determining the cross-sectional area of the filaments, microscope measurements of the diameter were made at five positions along the length of the Dacron test samples for determining Q. The values of G based on both the vibroscope and microscope methods are included in Table 2, and the data indicate close agreement between the two methods for measuring the cross-sectional area of the filaments.

Table 1.

Elastic Moduli for Nylon 66 Filaments of Various Draw Ratios

E (Young's Modulus - Extension)

Draw Ratio	Filament Cross-sectional Area (μ^2)		Frequency Range (cycles/sec)	E ($gm\ cm^{-2}$)$\times 10^{-6}$	
1	2694	± 191	-	8.8	± 0.4
2	1369	352	-	18.3	1.5
3	1055	102	-	24.0	1.1
4	789	228	-	33.9	2.2
5	608	97	-	42.8	4.1
6	561	62	-	51.8	5.0

Q (Young's Modulus - Bending)

				Q ($gm\ cm^{-2}$)x10-6	
1	2660	± 186	284 - 423	16.4	± 1.6
2	1846	407	239 - 1075	21.0	7.2
3	1122	112	305 - 709	33.9	2.5
4	788	233	285 - 454	42.6	3.1
5	609	112	274 - 401	50.3	4.9
6	560	57	285 - 464	57.0	5.5

Range of Sample Length = 0.32 - 0.55 cm; Cross-sectional area determined on four filaments for each draw ratio.

G (Torsional Modulus)

				G ($gm\ cm^{-2}$)$\times 10^{-6}$	
1	2713	± 190	187 - 224	5.1	± 0.3
2	1640	449	94 - 182	4.9	0.4
3	1126	105	91 - 140	5.6	0.7
4	796	236	55 - 140	5.3	1.4
5	606	104	52 - 106	5.9	0.6
6	570	56	54 - 135	6.1	0.8

Range of Cross-bar length = 0.20 - 0.41 cm; $(1/\ell_1 + 1/\ell_2)$ = 0.494 - 0.535 cm^{-1}.

Table 2.

Elastic Moduli for Dacron Filaments of Various Draw Ratios

E (Young's Modulus - Extension)

Draw Ratio	Filament Cross-sectional Area (μ^2)		Frequency Range (cycles/sec)	E (gm cm^{-2})x10^{-6}	
1	2748 ±	210	-	22.0 ±	1.8
2	1876	112	-	28.6	4.1
3	905	111	-	81.0	16.3
4	754	65	-	125.0	11.4
5	601	116	-	130.3	32.1
6	512	35	-	140.4	15.5

Q (Young's Modulus - Bending)
Filament Cross-sectional Areas Measured Vibroscopically

Draw Ratio	Filament Cross-sectional Area (μ^2)		Frequency Range (cycles/sec)	Q (gm cm^{-2})x10^{-6}	
1	2746 ±	405	222 - 730	23.9 ±	2.0
2	1700	503	165 - 371	31.9	12.5
3	885	132	237 - 312	93.7	8.6
4	759	48	229 - 409	117.6	6.8
5	579	82	300 - 407	142.4	27.0
6	516	43	238 - 363	138.2	17.0

Range of Sample Length = 0.53 - 0.76 cm; cross-sectional area determined on four filaments for each draw ratio.

Q (Young's Modulus - Bending)
Filament Cross-sectional Areas Measured Microscopically

Draw Ratio	Filament Cross-sectional Area (μ^2)		Frequency Range (cycles/sec)	Q (gm cm^{-2})x10^{-6}	
1	2689 ±	137	222 - 730	24.3 ±	2.3
2	1441	339	165 - 371	42.6	17.1
3	873	143	237 - 312	83.2	17.6
4	743	166	229 - 409	109.6	13.7
5*	571	38	300 - 407	131.9	28.6
6	500	33	238 - 363	127.5	14.6

Range of Sample Length = 0.53 - 0.76 cm. *Five filaments measured.

G (Torsional Modulus)

Draw Ratio	Filament Cross-sectional Area (μ^2)		Frequency Range (cycles/sec)	G (gm cm^{-2})x10^{-6}	
1	2773 ±	408	270 - 437	9.5 ±	0.3
2	1734	230	155 - 161	6.2	2.9
3	941	159	88 - 122	7.2	1.1
4	754	57	75 - 120	8.5	0.7
5	568	85	54 - 70	7.5	1.0
6	512	42	50 - 53	8.2	0.6

Range of Cross-bar Length = 0.30 - 0.42 cm; $(1/\ell_1 + 1/\ell_2)$ = 0.556 - 1.020 cm^{-1}.

The torsional moduli for nylon 66 and Dacron are not affected appreciably by the filament draw ratio. This result, which is in striking contrast to the behavior of E and Q with draw ratio, may indicate that the drawing process increases the torsional modulus near the core of the filament and has little effect on the modulus of the material near the surface.

Values for the ratio E/3G and Q/3G for nylon 66 and for Dacron are given in Table 3 for the complete draw ratio range. Both E/3G and Q/3G increase from near unity for the undrawn filaments to about three for nylon 66 and to greater than five for Dacron at a draw ratio of six. For a homogeneous isotropic material the relation between Q and G should be

$$\frac{Q}{G} = 2(1 + \sigma) \qquad \text{- - - - - - - - - - - -} \qquad (4)$$

where σ is the Poisson's ratio for the material. If Poisson's ratio is 1/4, E/3G = 0.83; if Poisson's ratio is 1/2, E/3G = 1. Q/3G is found to be 0.84 and 1.07 for undrawn Dacron and nylon 66 respectively; for higher draw ratios the values of Q/3G (and E/3G) exceed unity. The lower values of E/3G directly reflect the influence of time-dependent effects in the quasi-static measurement of E. For this reason the ratio E/3G is listed only for comparison with Q/3G, which represents the ratio of two dynamic moduli. Because of the effects of crystallite formation and orientation in the drawing process the departure of this ratio from unity is not surprising and reflects an increasing filament anisotropy with draw ratio. For nylon 66 at draw ratio four Q/3G is 2.75, a value which agrees well with the factor 2.9 found by Hammerle and Montgomery [6] when comparing the Young's and torsional moduli of

Table 3.

E/3G and Q/3G for Nylon 66 and Dacron Filaments of Various Draw Ratios

Draw Ratio	E/3G		Q/3G (Vibroscope)		Q/3G (Microscope)	
NYLON 66						
1	0.58	± 0.05	1.07	± 0.11		
2	1.25	0.16	1.43	0.49		
3	1.44	0.18	2.04	0.30		
4	2.19	0.65	2.75	0.36		
5	2.43	0.42	2.86	0.32		
6	2.84	0.62	3.13	0.47		
DACRON						
1	0.77	± 0.07	0.84	± 0.07	0.85	± 0.09
2	1.64	0.76	1.76	0.65	2.55	1.56
3	3.78	0.62	4.38	0.40	3.92	0.88
4	4.89	0.38	4.62	0.41	4.30	0.58
5	5.61	1.42	6.24	1.13	5.80	1.40
6	5.70	0.62	5.62	0.77	5.18	0.64

drawn nylon by stress relaxation and box-distributional methods. The increasing departure of E/3G and Q/3G from unity with increasing draw ratio shows that caution must be used in estimating the value of the Young's modulus from the torsional modulus and vice versa for inhomogeneous and/or oriented filaments.

The high values for the deviation of the means are due largely to inhomogeneities in the filaments introduced by drawing. The influence of these inhomogeneities on the derived moduli is shown for nylon 66 in Figures 8, 9, and 10 where E, Q, and G, respectively, for the various draw ratios are plotted against the reciprocal of the filament cross-sectional area on a log-log basis; similar data for Dacron are given in Figures 11, 12, and 13. In Figure 12 the values for the Young's modulus from bending are plotted for both the vibroscope and microscope measurements of filament cross-sectional area. The least-mean-squares lines are plotted in Figures 8-13,

inclusive, for E, Q, and G vs. reciprocal cross-sectional area for nylon 66 and Dacron; values for the slopes of these lines are listed in Table 4.

Table 4.

Slopes of Least-Mean-Squares Lines for Elastic Moduli of Nylon 66 and Dacron versus Reciprocal of Filament Cross-sectional Area [Based on log modulus = b log (1/filament area)]

Elastic Modulus	$b \pm t_{0.05} \cdot \sigma_b$			
	Nylon 66		Dacron	
E	1.064 ±	0.086	1.218 ±	0.097
Q (vibroscope)	0.788	0.103	1.192	0.126
Q (microscope)			1.085	0.098
G	0.105	0.081	0.001	0.143

To compare with nylon 66 and Dacron, the data for the elastic moduli of 1-mil tungsten wire are presented in Table 5. The values reported are means of measurements on four samples in the cases of E and G and eight in the case of Q. A plot of the bending frequencies of the fundamental and first overtone vs. the square of the reciprocal filament length (Figure 14) shows how well the response predicted by Equation 3 is followed by tungsten wire. The mean deviations for these moduli are seen to be considerably lower than those for the nylon 66 and Dacron filaments reported above, and the values of E and Q are in much better agreement, indicating only a small influence of creep and stress relaxation in the measurement of E. Moreover, the values of E/3G and Q/3G show that the Poisson's ratio for this tungsten wire probably has a value between 1/4 and 1/2.

Table 5.

A. Elastic Moduli of 1-mil Drawn Tungsten Wire

E (Young's Modulus - Extension)

Sample*	Filament Cross-Sectional Area (μ^2)	Approximate Test Length (cm)	Extension Rate (%/min.)	E $(gm\ cm^{-2})x10^{-8}$
1	504 ± 2	10.0	0.5	37.3 ± 0.1**
2	509 9	3.7	1.3	42.0 1.4

Q (Young's Modulus - Bending)

		Test Length Range (cm)	Frequency Range (cps)	Q $(gm\ cm^{-2})x10^{-8}$
1***	504 ± 2	0.51 - 0.58	457 - 578	35.5 ± 0.7
2***	506 6	1.00 - 1.08	137 - 155	38.5 0.4

G (Torsional Modulus)

		Cross-Bar (cm)	$(1/\ell_1 + 1/\ell_2)$ (cm^{-1})		G $(gm\ cm^{-2})x10^{-8}$
1	504 ± 2	0.37 - 0.42	0.546 - 0.568	630 - 740	14.3 ± 0.5
2	513 2	0.36 - 0.40	0.416 - 0.419	575 - 672	13.9 0.5

B. Ratio of Elastic Moduli for 1-mil Drawn Tungsten Wire

	E/3G	Q/3G
1	0.87 ± 0.02	0.83 ± 0.01
2	1.00 0.03	0.92 0.02

* Samples 1 and 2 are obtained, respectively, from Palmer Physical Laboratory, Princeton University, Princeton, N.J., and the Cleveland Wire Works, Lamp Division, General Electric Company, Cleveland, Ohio.

** E measured on different test samples than used for Q and G.

*** Cross-sectional area determined on four filaments for each sample.

Conclusions

The work reported here leads to the following conclusions:

1. A dynamic method based on the electrostatic vibroscope has been developed and applied to determine the bending and torsional moduli of nylon 66 and Dacron filaments in the range of draw ratios from one to six, inclusive.

2. For nylon 66 and Dacron the Young's modulus (Q) from bending was found to increase by a factor of 3.5 and 5.8, respectively, for draw ratios from one through six.

3. For both materials the torsional modulus (G) changes only slightly with draw ratio.

4. Quasi-static measurements of the Young's modulus (E) from extension show that is is generally lower than the Young's modulus (Q) from bending at the same draw ratio; the difference is greater for nylon 66 than for Dacron and is more pronounced at the low draw ratios, indicating that effects of creep and stress relaxation operate to decrease the modulus when measured under quasi-static conditions.

5. The values of E/3G and Q/3G increase with draw ratio; at draw ratio six, E/3G and Q/3G are 2.84 and 3.13 for nylon 66, and 5.70 and 5.62 for Dacron. This change in the modulus ratio indicates an increasing degree of filament anisotropy with increasing draw ratio.

6. The high values of the mean deviations for Q and G for nylon 66 and Dacron result from filament inhomogeneities introduced by the drawing process. Comparable measurements on 1-mil drawn tungsten wires for Q and G show that their mean deviations are significantly lower than those for nylon 66 and Dacron and reflect the higher degree of uniformity of the tungsten wires.

Acknowledgments

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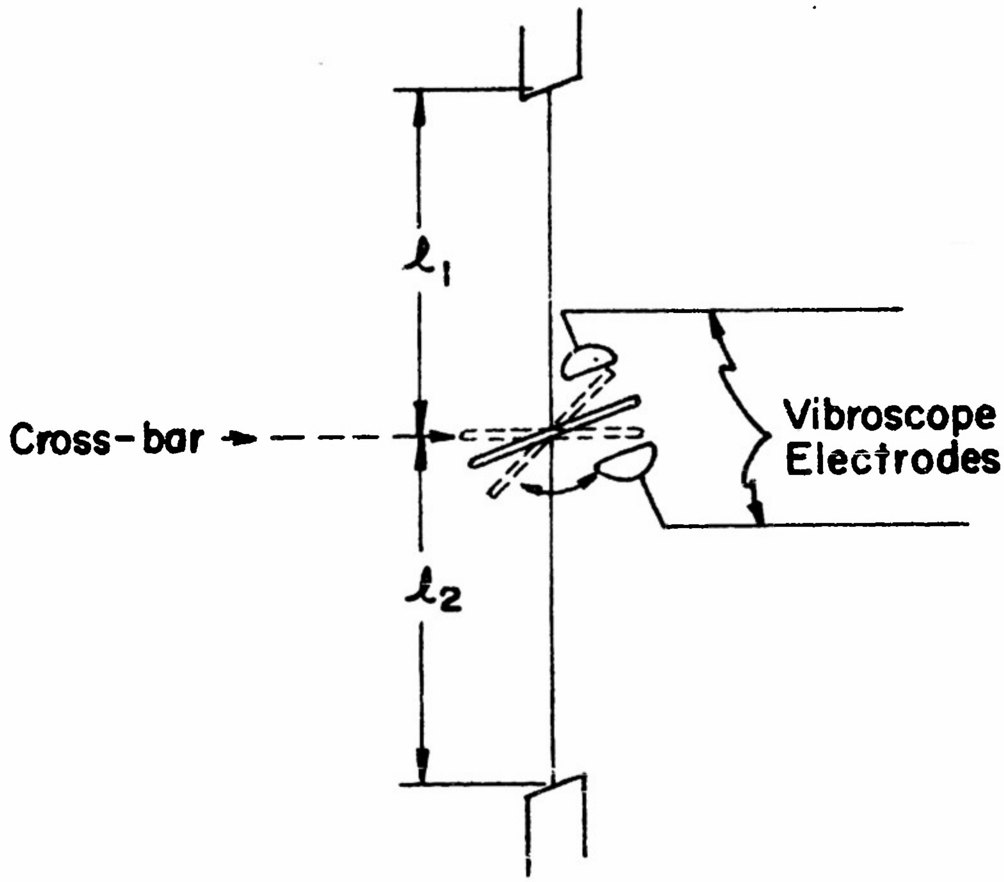

Fig. 1. Sketch of vibroscope method for obtaining torsional modulus of filaments.

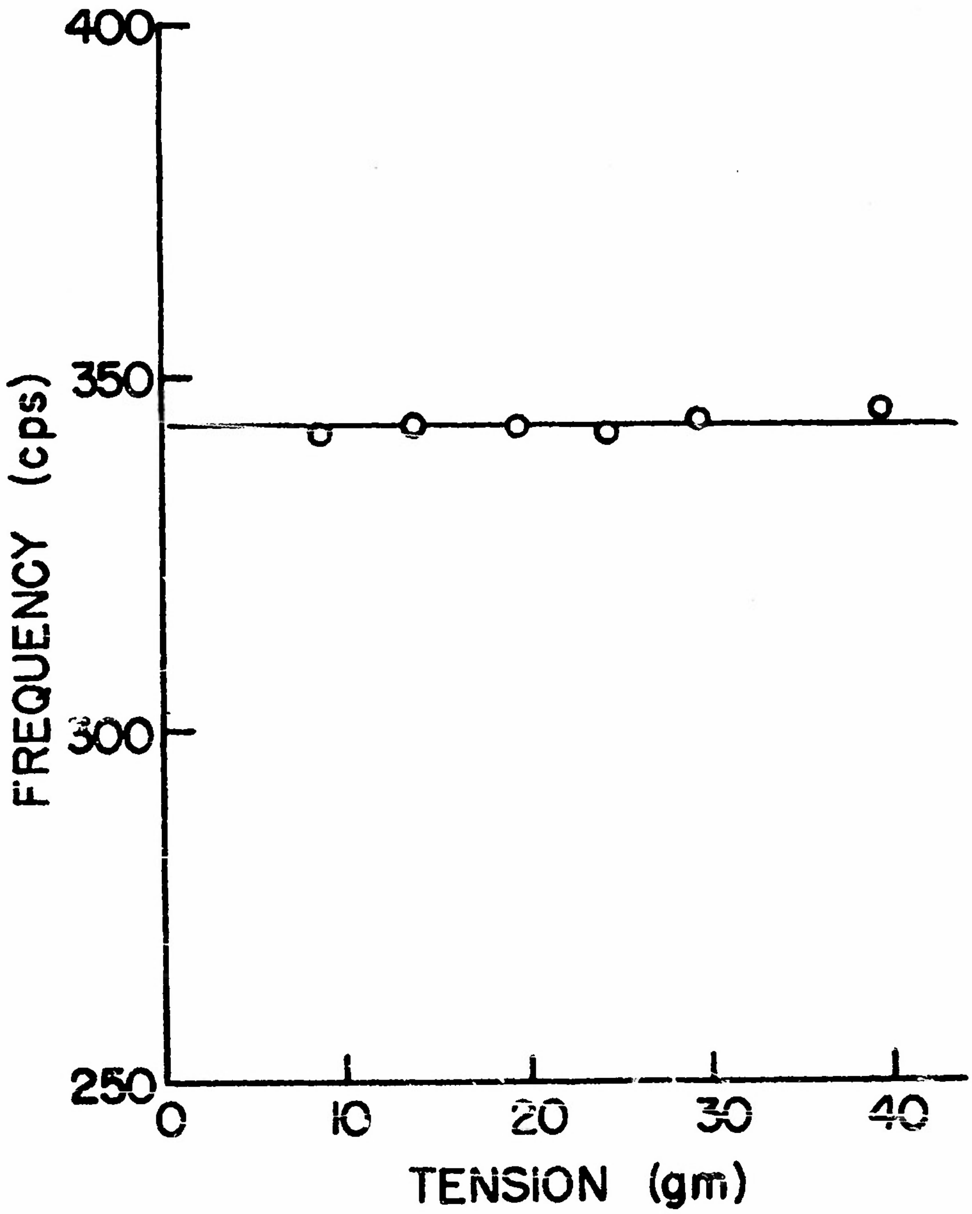

Fig. 2. Effect of filament tension on torsional frequency (30-denier drawn nylon 66).

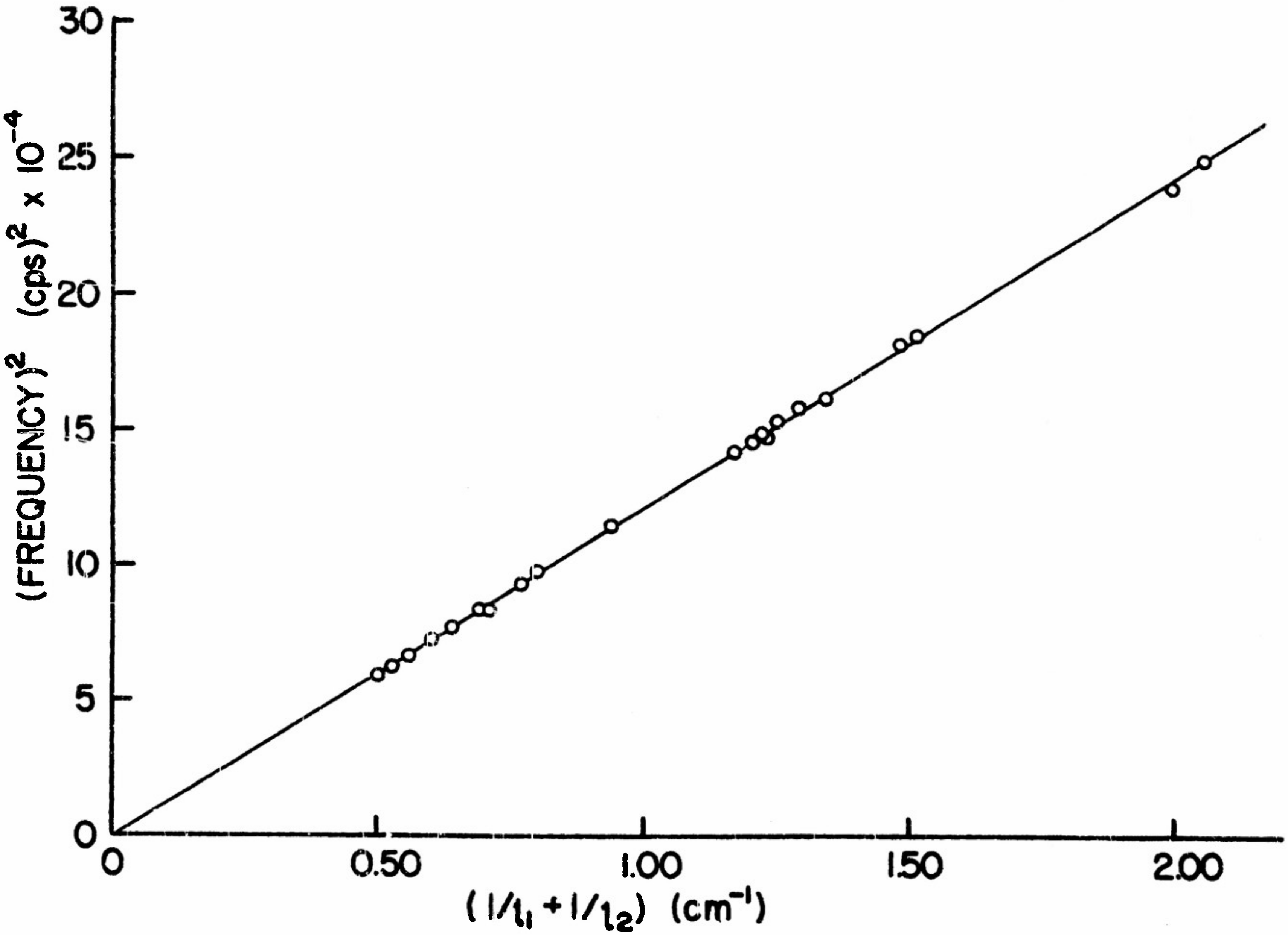

Fig. 3. Effect of length of filament and cross-bar position on torsional frequency (30-denier drawn nylon 66).

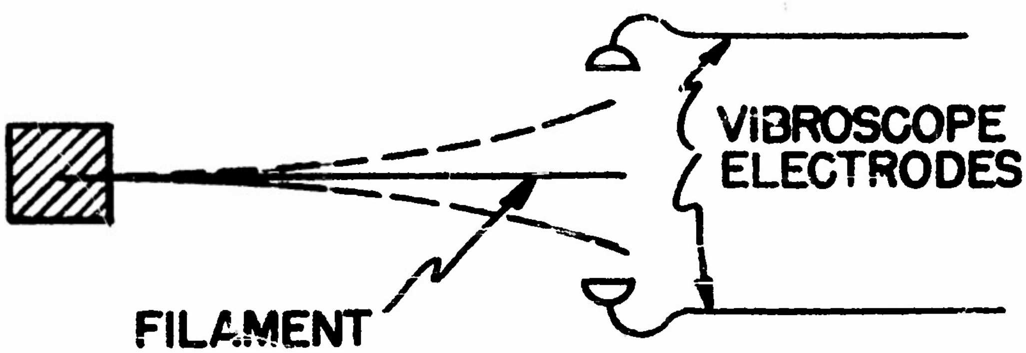

Fig. 4. Sketch of vibroscope method for obtaining the bending modulus of filaments.

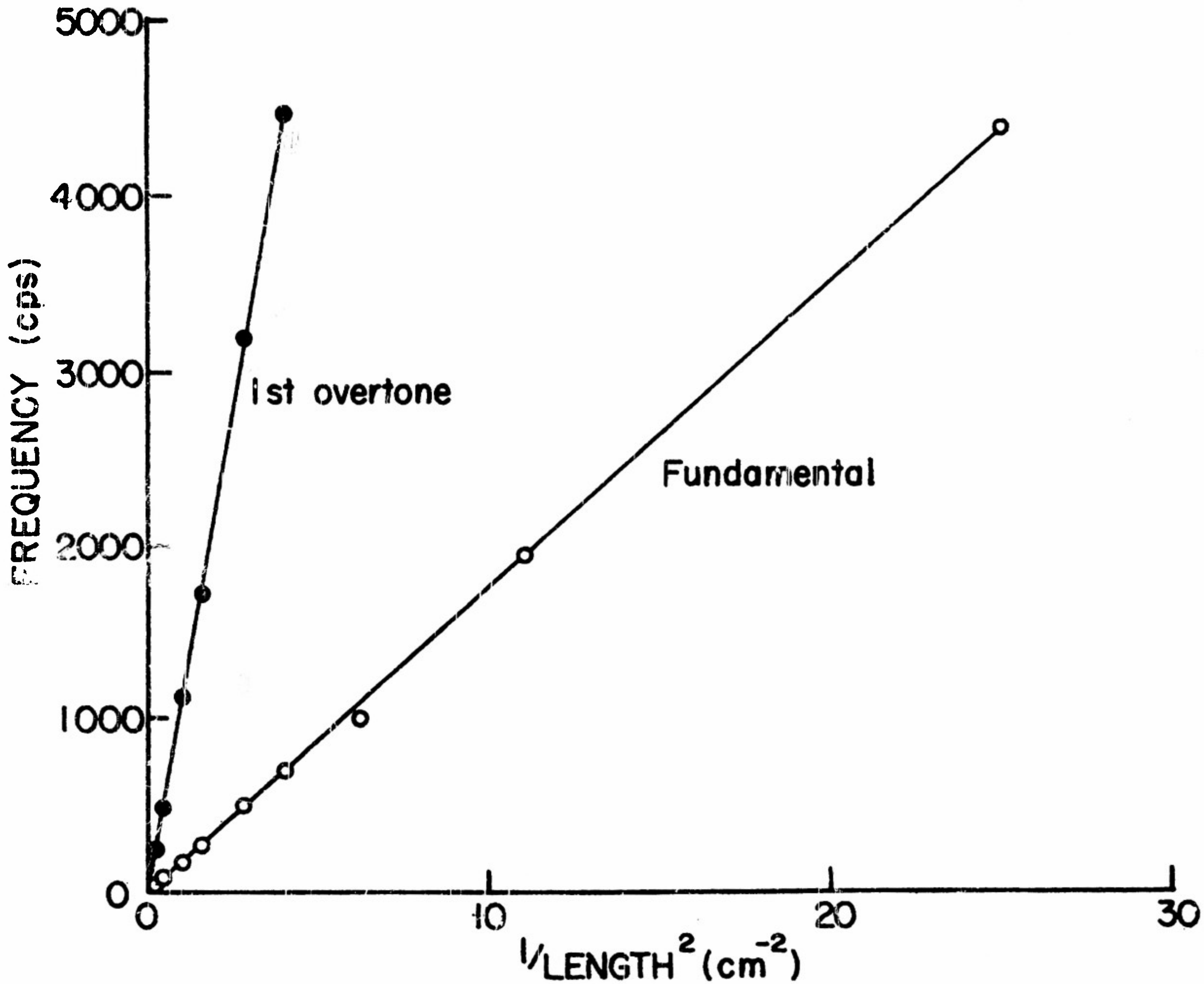

Fig. 5. Effect of filament length on the bending frequency of the fundamental and first overtone (30-denier drawn nylon 66).

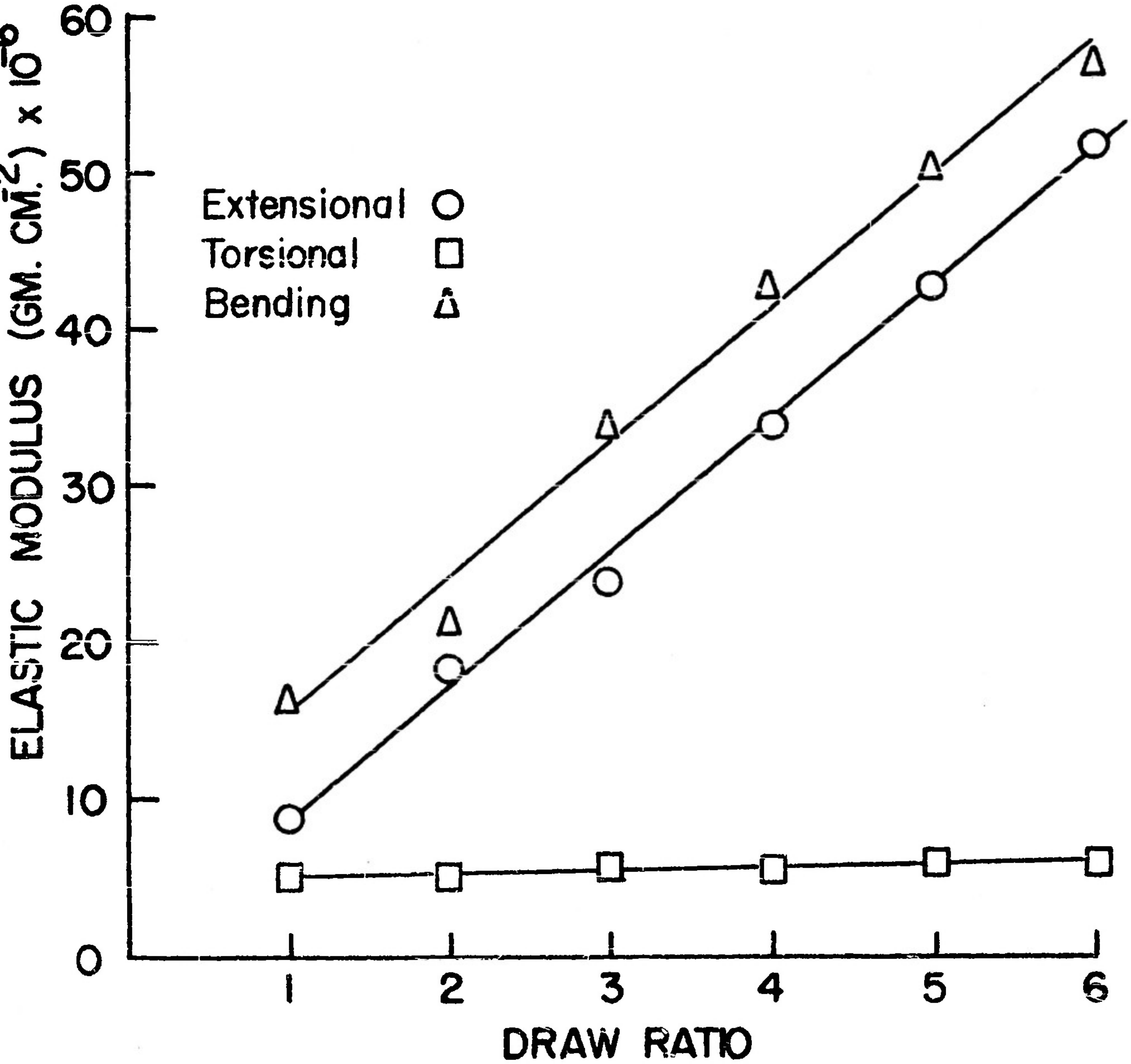

Fig. 6. Elastic moduli of nylon 66 of various draw ratios.

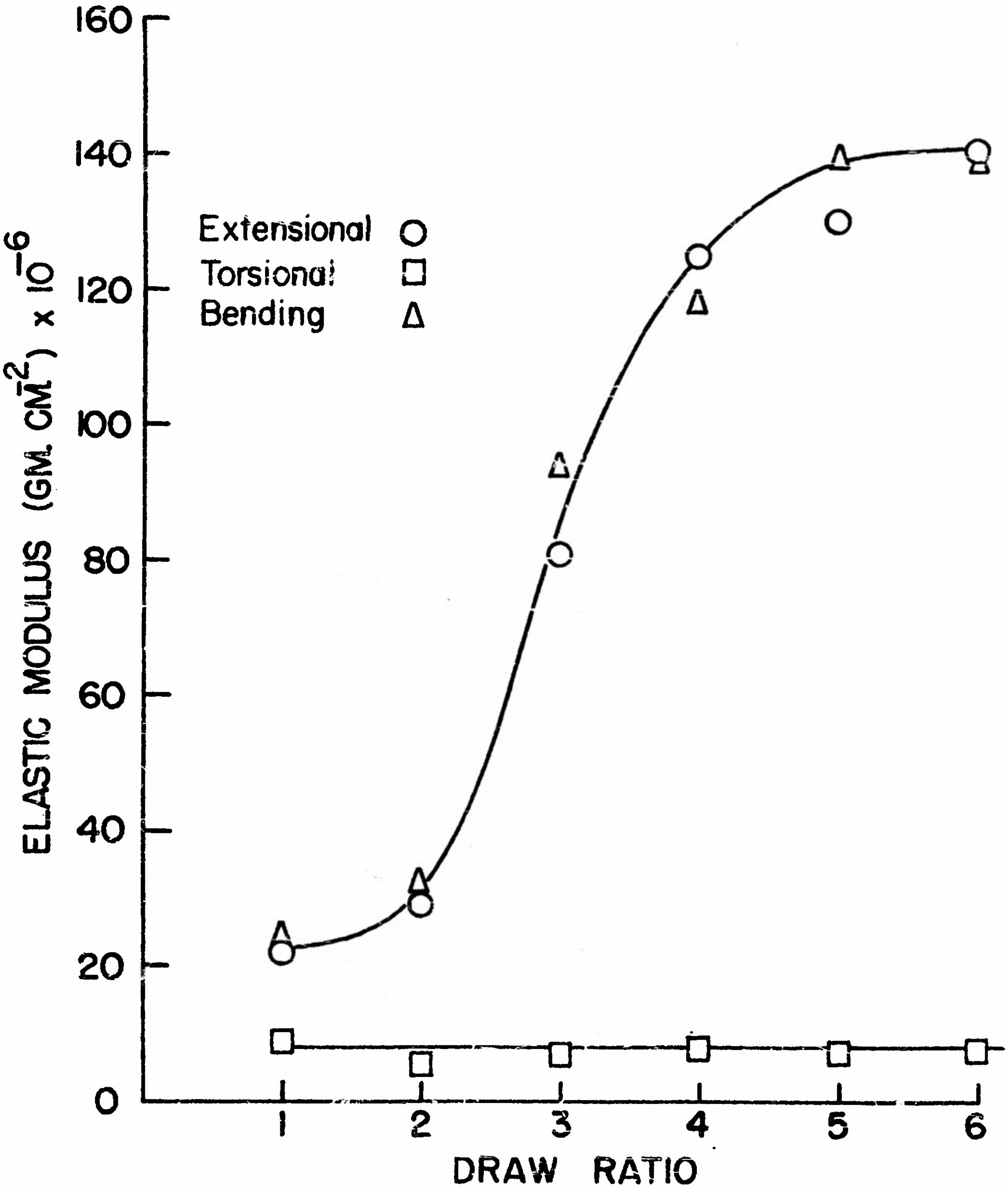

Fig. 7. Elastic moduli of Dacron of various draw ratios.

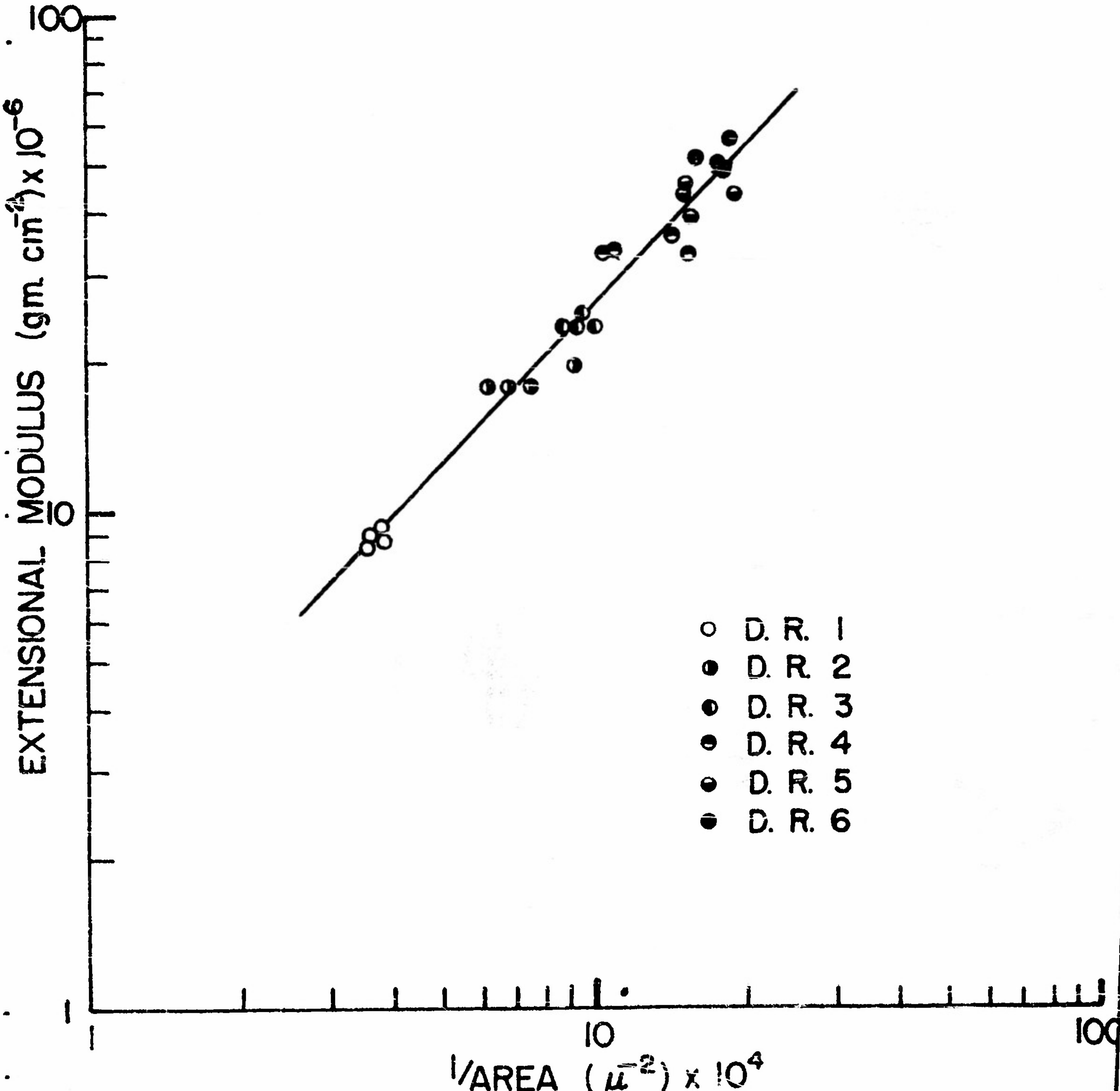

Fig. 8. Extensional modulus of nylon 66 vs. reciprocal cross-sectional area of filaments at various draw ratios.

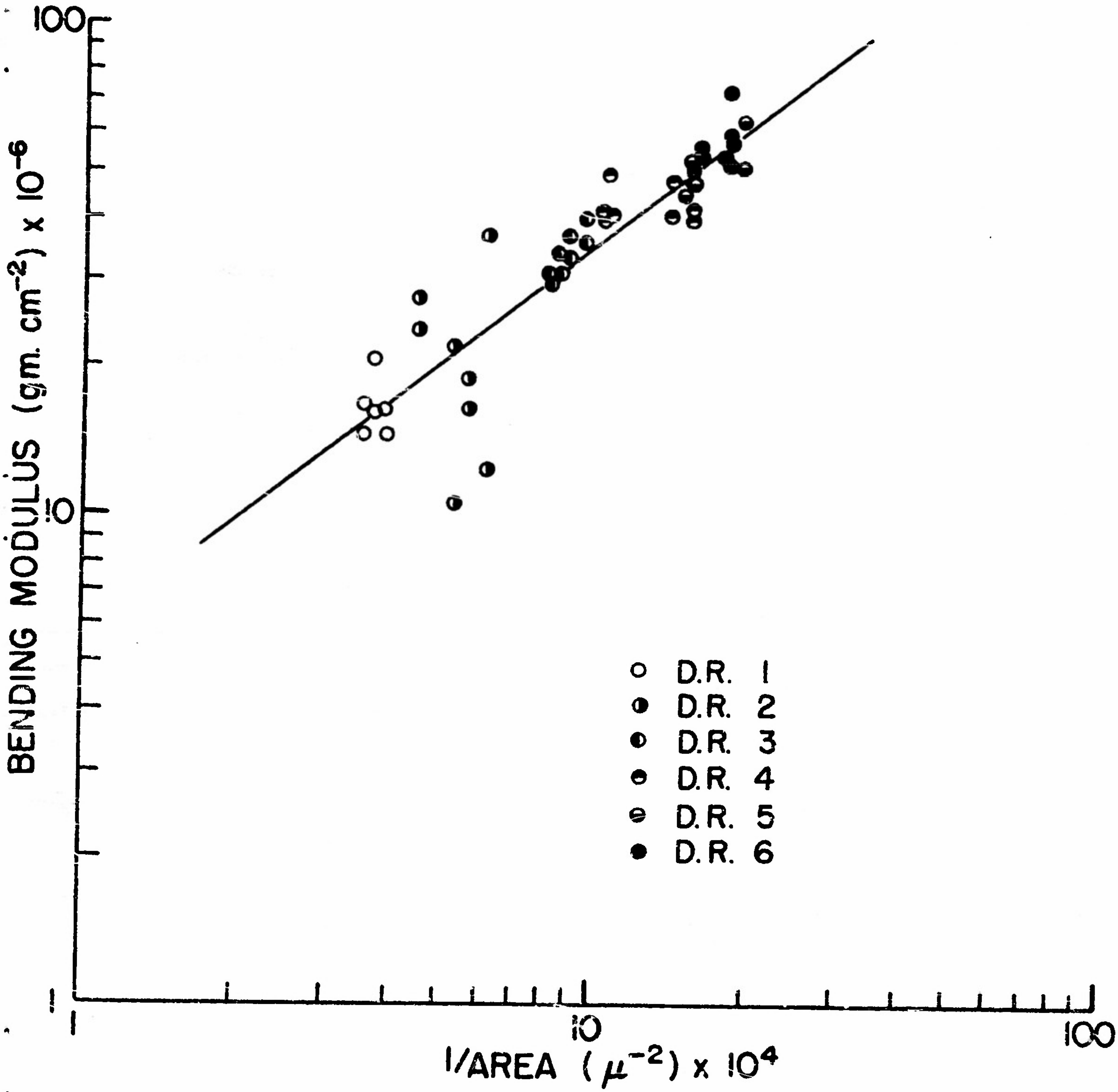

Fig. 9. Bending modulus of nylon 66 vs. reciprocal cross-sectional area of filaments at various draw ratios.

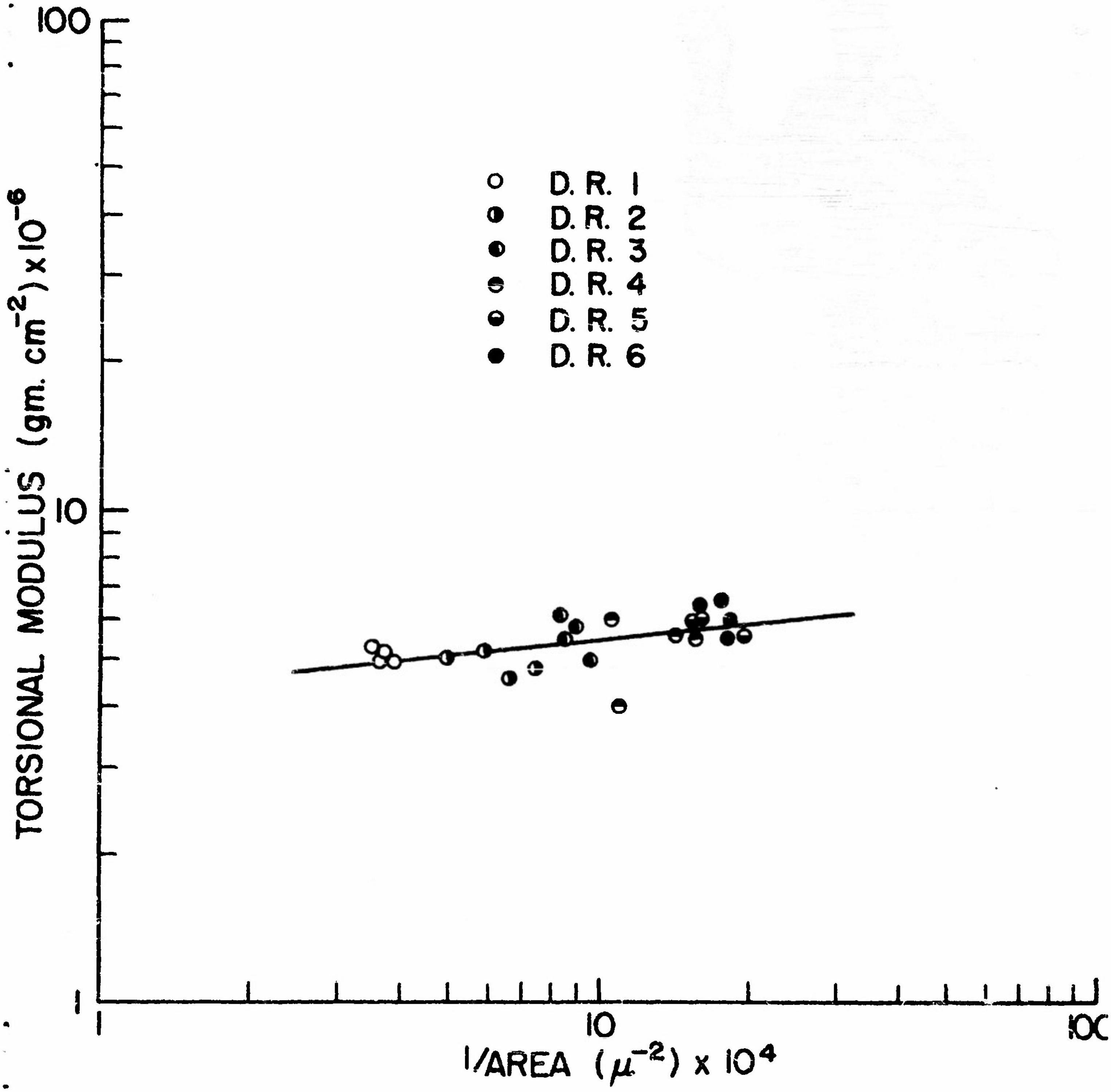

Fig. 10. Torsional modulus of nylon 66 vs. reciprocal cross-sectional area of filaments at various draw ratios.

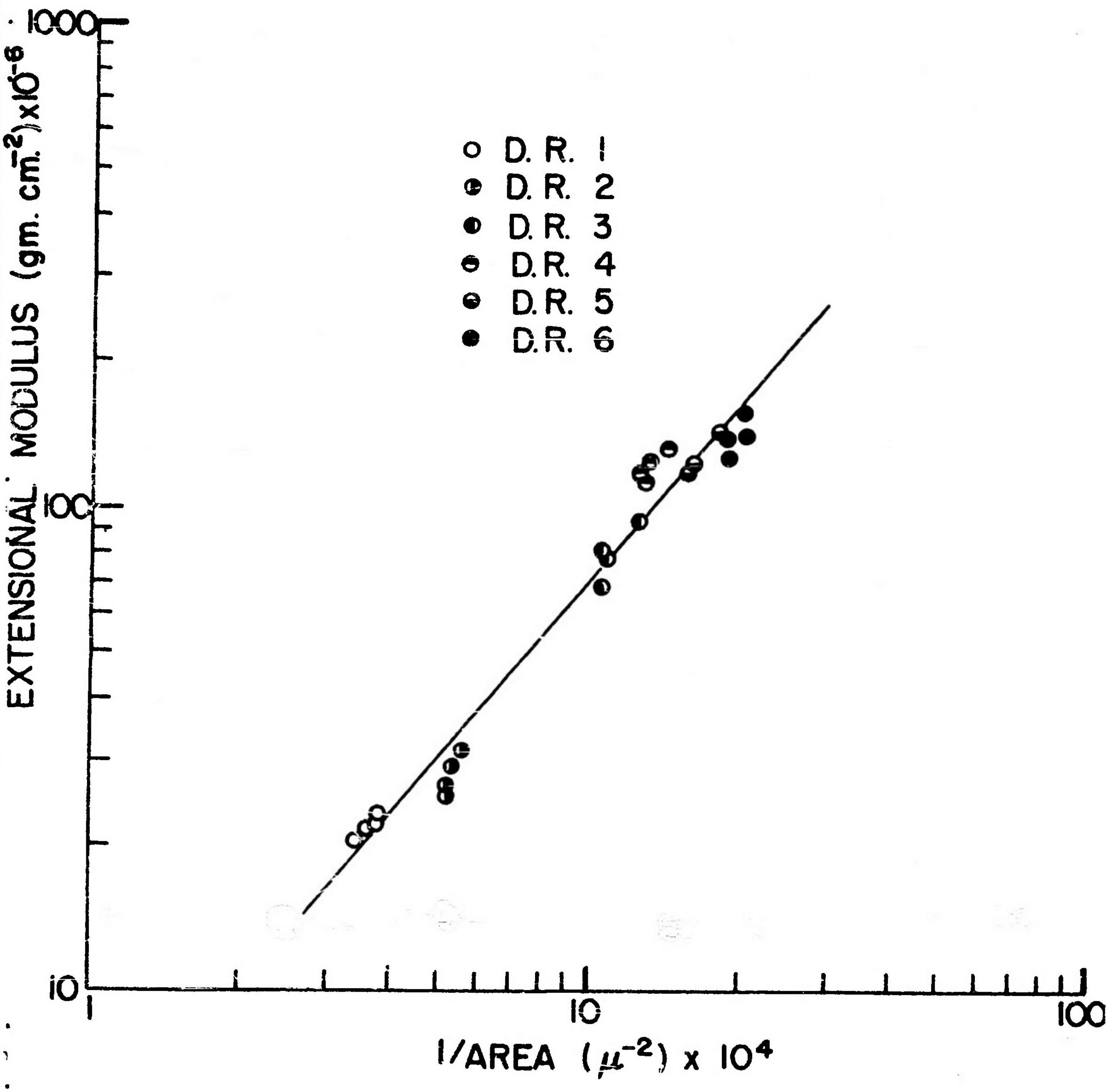

Fig. 11. Extensional modulus of Dacron vs. reciprocal cross-sectional area of filaments at various draw ratios.

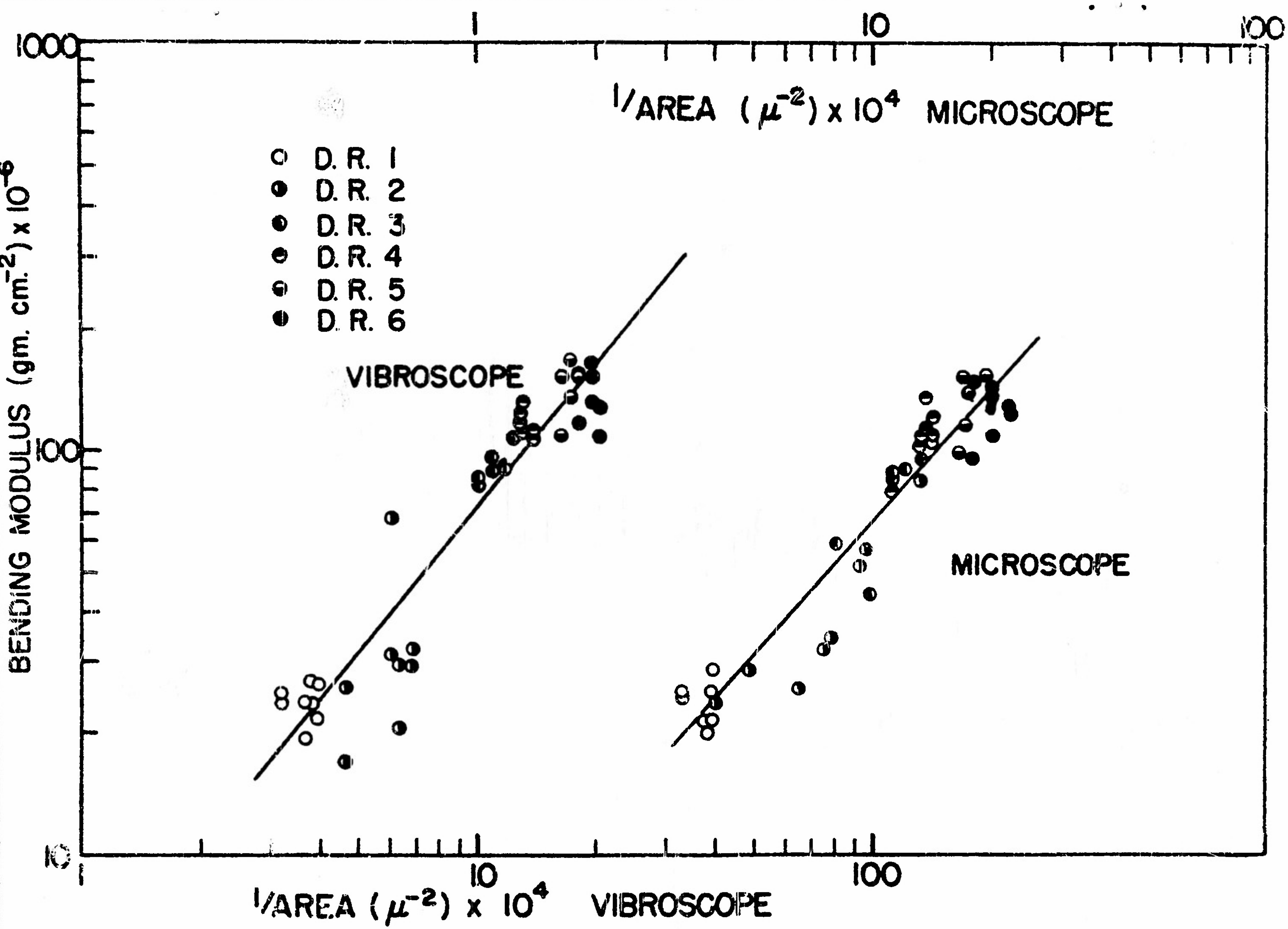

Fig. 12. Bending modulus of Dacron vs. reciprocal cross-sectional area measured by vibroscope and microscope on filaments at various draw ratios.

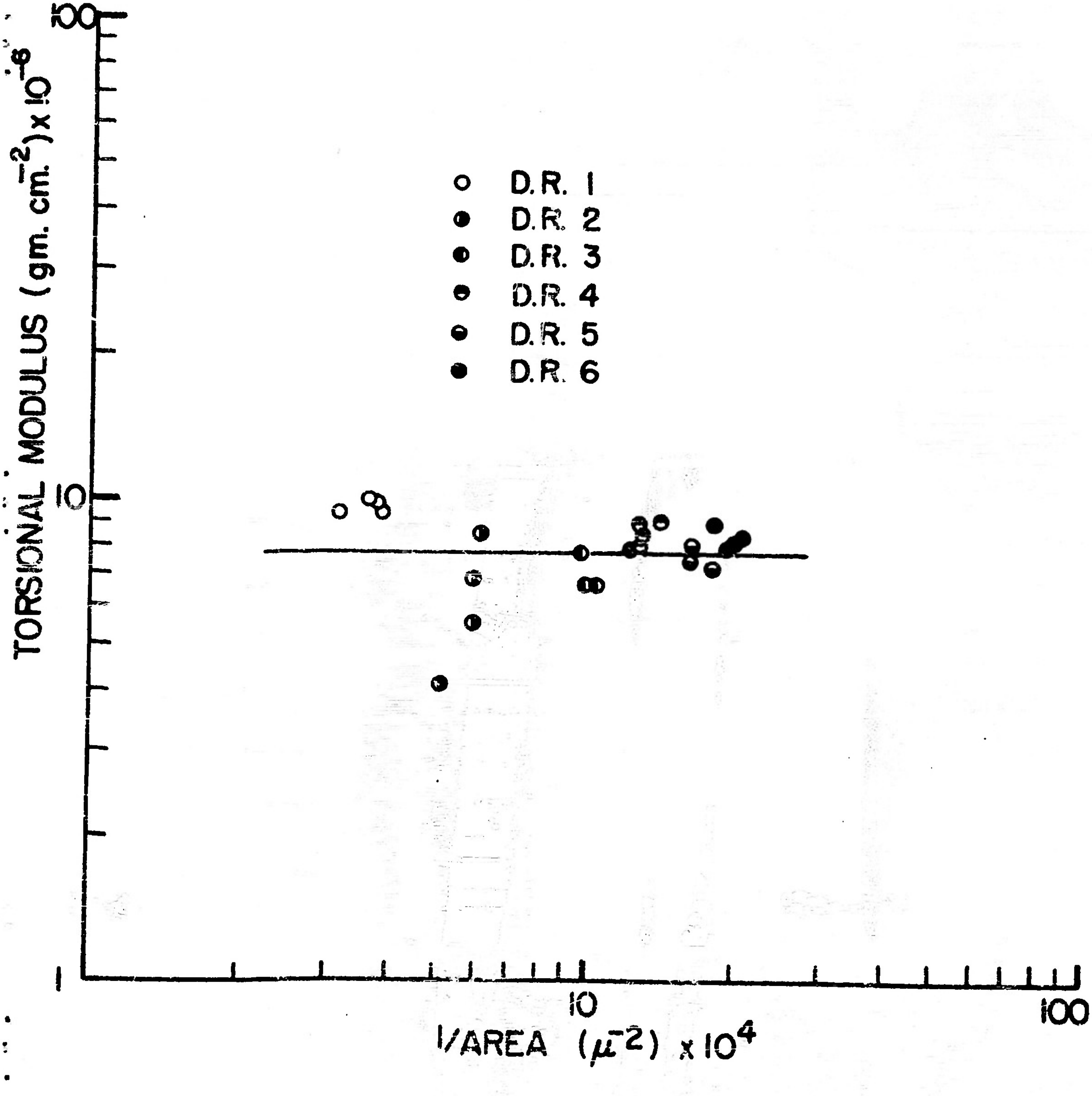

Fig. 13. Torsional modulus of Dacron vs. reciprocal cross-sectional area of filaments at various draw ratios.

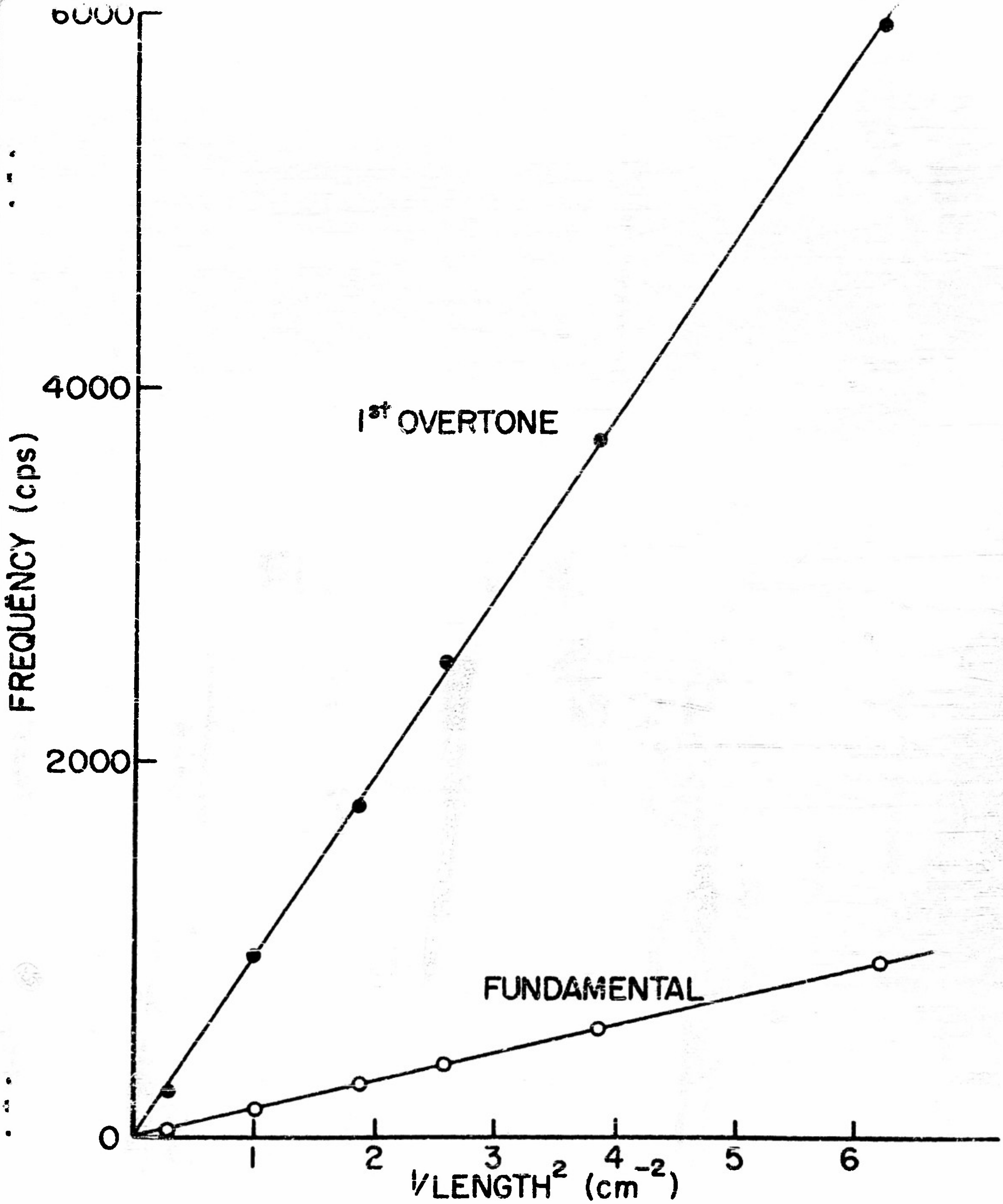

Fig. 14. Effect of filament length on the bending frequency of the fundamental and the first overtone (1-mil drawn tungsten wire).